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SHORT NOTE ON ULTRAMAFIC GRANULITES IN THE ONGUL ISLANDS AREA, EAST ANTARCTICA

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Abstract: Ultramafic granulites in the East and West Ongul Islands area are grouped into two types, A and B. One of the fundamental criteria of the grouping is that type A does not yield plagioclase and type B does. Type A is characterized by the abundance of orthopyroxene and clinopyroxene and by the lack of plagioclase and garnet. It occasionally yields olivine. Type B is characterized by the presence of plagioclase and/or garnet and by the poverty in pyroxenes. In common cases, type A tends to occur as massive isolated blocks or pods in the surrounding gneisses, while type B as concordant sheets or layers showing a distinctly foliated structure. Between these two types, chemical characteristics of main constituent minerals such as orthopyroxene, clinopyroxene and hornblende are different from each other. Those in type A are comparatively more magnesian and less aluminous. Metamorphic temperature estimated from the pairs of orthopyroxene and clinopyroxene of both types is as high as around 800°C. Pressure condition is calculated based upon the associations of garnet, pyroxenes and plagioclase of type B to give the values around 7.5 kb. The essential difference between the two types is inferred to reflect the difference in petrological characters of original rocks.

1. Introduction

The area of East and West Ongul Islands has been argued to be the granulite-facies metamorphic terrain since the pioneer works by BANNO *et al.* (1964) and SUWA (1968). Metabasites in the area have been called by various names such as amphibolite, hornblendite, pyroxinites (orthopyroxenites and clinopyroxinites), eclogites, anorthosites and so on (KANO, 1982). In general, they are characterized by a dark green color reflecting the abundance of mafic minerals. In this paper the author will deal with those metabasites which carry mafic minerals of around 70 modal percents or more, and hereafter they are called ultramafic granulites. The results of investigations on the members of anorthosites which must be important to clarify the petrogenetic significance of the metabasites in the area will be given in a separate paper (SUZUKI, in preparation).

The ultramafic granulites in the area show various kinds of lithofacies and mode of field occurrence. The mineralogical characteristics of them have not yet been clarified. In this paper, will be given the grouping of the ultramafic granulites based upon mineralogical characteristics and mode of field occurrence. The metamorphic conditions suggested by the granulites are also shown.

2. Geological Outline

The metamorphic rocks of the area around East and West Ongul Islands, where

Syowa Station is situated, have been investigated by many Japanese geologists (KIZAKI, 1964; YANAI *et al.*, 1974a, b). It has been clarified that the area is underlain by various kinds of metamorphites, such as pyroxene gneiss (charnockite), hornblende gneiss, garnet gneiss, garnet-biotite gneiss and granitic gneiss. So-called metabasites including ultramafic granulites concerned are closely associated with the metamorphites shown above. Plutonic rocks of gneissose granite, microcline granite and pegmatite are associated and most of them are considered to be post-kinematic and have been active about 500 Ma ago causing some secondary changes in mineralogy to the surrounding gneisses (HIROI and ONUKI, 1985).

Metamorphic conditions in the area have been discussed by many authors to be concluded that the area underwent the granulite-facies metamorphism which is progressively graded up from the amphibolite-facies condition in the Prince Olav Coast (HIROI *et al.*, 1983; SHIRAISHI *et al.*, 1984; SUZUKI, 1985). Moreover, MOTOYOSHI (1985) and MOTOYOSHI *et al.* (1985) have clarified that the metamorphic conditions increase toward the southern part of Lützow-Holm Bay from east to west. Therefore, the Ongul Islands area situated in the eastern part of the Lützow-Holm Bay region represents the lower grade part in the granulite-facies metamorphic terrain of the region.

3. Grouping and Mode of Field Occurrence of Ultramafic Granulites

3.1. Modal composition

Based upon the mineral parageneses, ultramafic granulites in the East and West Ongul Islands area can be grouped into two types, A and B. Type A does not yield plagioclase but type B does. Between types A and B, modal composition of main constituent minerals is different from each other (Table 1).

Type A is characterized by the abundance of orthopyroxene and clinopyroxene and by the lack of plagioclase and garnet. The total amount of pyroxenes exceeds 40% by volume. Orthopyroxene is usually larger in amount than clinopyroxene. One specimen (77011411) collected at Pollholmen contains olivine with the modal amount of 27%. Hornblende is usually less than 30% in modal amount. The other constituent minerals are biotite and Fe-Ti oxides. Quartz is sometimes found in olivine-free rocks.

Type B is characterized by the appearance of plagioclase and/or garnet and poverty in orthopyroxene and clinopyroxene. Orthopyroxene is usually larger in amount than clinopyroxene as in the case of type A. The content of hornblende is variable among specimens ranging from 2 to 70 in modal percent. Biotite and Fe-Ti oxides are usually associated. No olivine is found in type B. Quartz is sometimes found.

Figure 1 shows the difference in modal composition between two types. Garnet is found only in plagioclase-bearing specimens (type B), thus in the figure an apex is represented in terms of plagioclase+garnet. As is easily seen from the figure, type A is rich in pyroxenes and poor in hornblende, lacking plagioclase and garnet, while type B is poor in pyroxenes.

3.2. Mode of field occurrence

Ultramafic granulites in the area show variable modes of occurrence such as concordant sheets, isolated blocks, boudinaged bodies and so on.

Table 1. The difference of modal composition and mode of field occurrence between two types of ultramafic granulites in East and West Ongul Islands area.

Sp. No.	Locality	Modal composition										Mode of field occurrence	
		Ol	Opx	Cpx	Hb	Gar	Biot	Pl	Qz	Opaque	Others	Occurrence (size; m/m)	Country rock
Type A													
77011411*	Pollholmen	26.8	34.3	7.0	30.0	—	—	—	—	0.4	1.5	Isolated block (0.3×0.3)	Charnockite
1509*	Eastern part of W.O.**	—	87.1	2.3	3.0	—	7.4	—	—	—	0.2	Isolated block (5×3)	Hornblende gneiss
1714*	Miharashi Peak, E.O.**	—	90.6	1.6	—	—	2.9	—	—	4.9	—	Isolated block (0.3×0.3)	Charnockite
1715*	Miharashi Peak, E.O.	—	67.1	19.9	6.4	—	6.0	—	0.6	—	—	Isolated block (0.3×0.3)	Charnockite
1719	Miharashi Peak, E.O.	—	96.3	—	0.4	—	2.5	—	—	0.8	—	Isolated block (0.3×0.4)	Hornblende gneiss
1801	Hatinosu Peak, E.O.	—	99.9	—	—	—	—	—	—	—	0.1	Lensoid body (0.3×1)	Type B granulite
Type B													
77011501*	Eastern part of W.O.	—	4.0	0.1	34.3	59.1	0.5	1.7	0.1	—	0.3	Sheet (0.4 m thick)	Charnockite
1504	Eastern part of W.O.	—	17.8	—	49.6	13.3	2.8	15.6	—	0.4	0.5	Sheet	Charnockite
1505*	Eastern part of W.O.	—	43.4	—	2.0	17.9	6.9	29.5	0.1	0.2	0.1	Sheet (0.3)	Charnockite
1506*	Eastern part of W.O.	—	19.3	—	46.5	—	1.7	30.2	0.1	0.1	2.2	Sheet (0.3)	Charnockite
1518	Central part of W.O.	—	11.1	—	52.7	—	3.1	31.8	0.1	1.2	—	Sheet	Charnockite
1606	Central part of W.O.	—	—	—	39.9	23.2	5.2	29.4	—	1.9	0.4	Sheet	Charnockite
1610*	Central part of W.O.	—	—	—	53.0	22.5	1.0	20.1	—	2.6	0.8	Boudinaged sheet (?) (5)	Garnet-biotite gneiss
1612*	Central part of W.O.	—	7.1	4.6	69.7	—	14.9	3.2	—	—	0.5	Boudinaged sheet (?) (5)	Garnet-biotite gneiss
1704*	Miharashi Peak, E.O.	—	2.6	—	52.7	3.9	12.2	28.3	0.1	0.2	0.1	Boudinaged sheet (1)	Charnockite
1706*	Miharashi Peak, E.O.	—	10.1	—	29.4	22.3	1.3	36.8	0.1	0.1	—	Sheet (0.3+)	Garnet gneiss
1707*	Miharashi Peak, E.O.	—	10.7	—	66.8	1.5	6.4	14.5	—	—	0.1	Boudinaged sheet	Garnet gneiss
1802	Hatinosu Peak, E.O.	—	6.0	—	39.6	39.1	5.4	8.7	—	—	1.1	Sheet (1.5+)	Garnet gneiss
1804*	Hatinosu Peak, E.O.	—	—	6.8	65.2	—	0.5	16.2	0.1	11.4	—	Sheet	Garnet gneiss
1806	Haitnosu Peak, E.O.	—	11.4	—	29.5	33.7	3.4	22.1	—	—	—	Sheet	Garnet gneiss

* Chemical analytical data of main constituent minerals are given in Appendix.
** W.O. and E.O. mean West and East Ongul Islands, respectively.

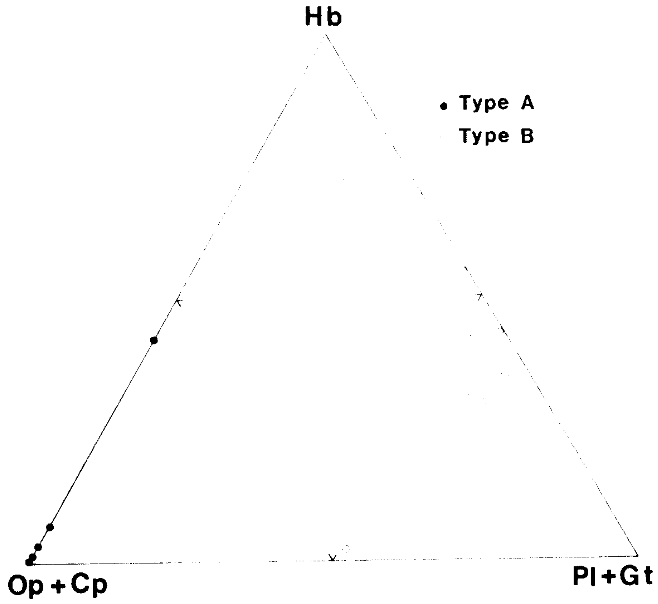

Fig. 1. *Modal composition of types A and B ultramafic granulites in terms of calcic amphiboles (Hb)-orthopyroxene (Op)+clinopyroxene (Cp)-plagioclase (Pl)+garnet (Gt).*

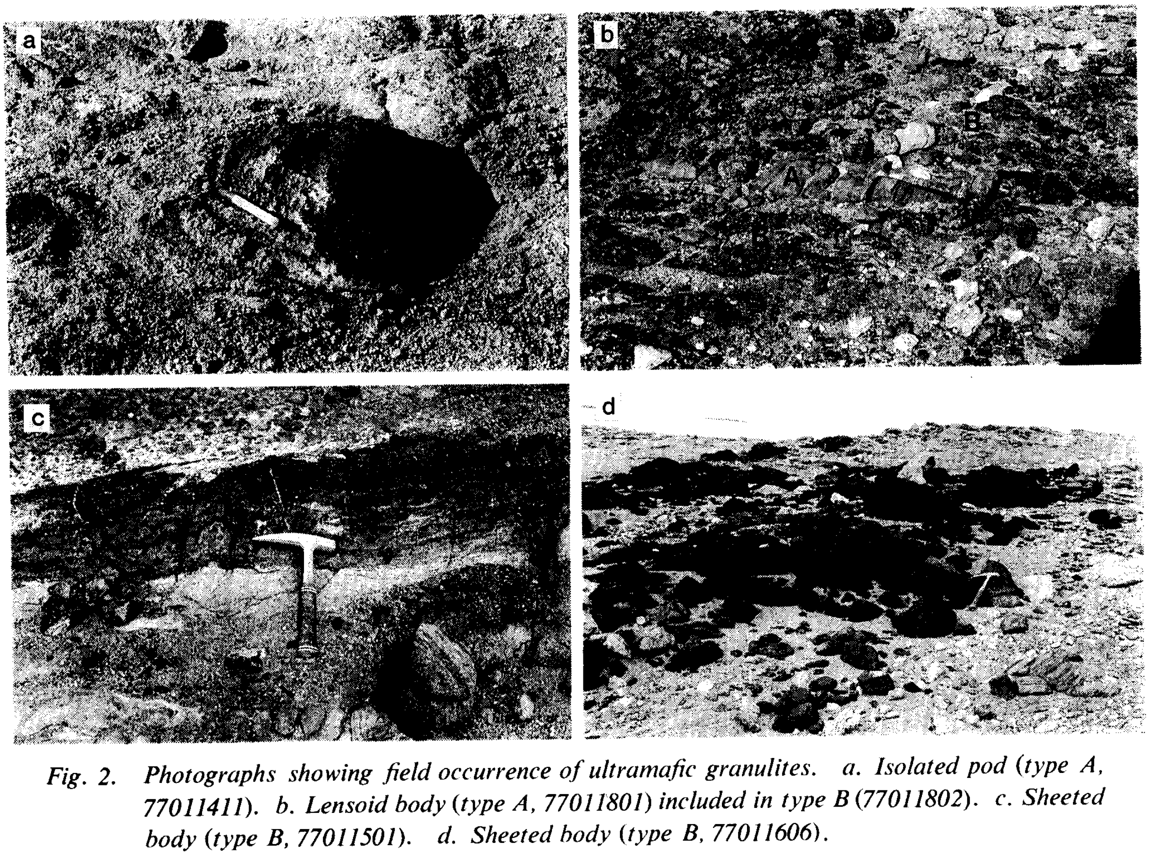

Fig. 2. *Photographs showing field occurrence of ultramafic granulites. a. Isolated pod (type A, 77011411). b. Lensoid body (type A, 77011801) included in type B (77011802). c. Sheeted body (type B, 77011501). d. Sheeted body (type B, 77011606).*

Generally speaking, types A and B show different modes of field occurrence as follows (Table 1). Type A is massive and has no distinctly foliated structure, and tends to occur as isolated lensoid blocks in the surrounding charnockite and gneisses, the long axes of the blocks being in the range of 0.3 to 5 m (Fig. 2). Meanwhile, type B commonly occurs as concordant sheets with the thickness ranging from 0.3 to a few meters (Fig. 2). It often shows distinct foliation which is commonly concordant with that developed in the surrounding gneisses. The foliation in type B is characterized by a layered structure reflecting the compositional banding. When type B occurs as a lensoid body, it is inferred to be the boudinaged one originated from a sheet.

Generally speaking, both types of ultramafic granulites are developed throughout the area concerned showing no tendency of spacial distribution. The species of associating gneisses, however, seem to be rather different between the two types (Table 1). Namely, type A tends to occur surrounded by such intermediate rocks as charnockite and hornblende gneisses. In a exceptional case a specimen (77011801) is found included in type B ultramafic granulite (Fig. 2). Meanwhile, type B occurs as sheets concordant with such paragneisses as garnet gneiss (quartzite-origin) and garnet-biotite gneiss (pelite-origin), as well as with charnockite.

The above-mentioned differences in mode of field occurrence must be significant but the petrogenetical bearing cannot yet be clarified.

4. Chemical Characteristics of Main Constituent Minerals of Ultramafic Granulites

Electron microprobe analyses of main constituent minerals were performed using JXA-5A (JEOL) at Hiroshima University and the representative analytical data are listed in Tables A-1 to A-6 in the Appendix. Distinct differences in chemical characteristics are observed in each constituent mineral between types A and B as shown in the following.

a) Olivine

Olivine is found only in one specimen of type A. It sometimes contains grains of hornblende and pyroxenes poikiloblastically. The composition is characterized by high forsterite molecules attaining to as high as 79%. Olivine is not found in type B and it is worthy of note that the association of olivine and plagioclase is not found in the ultramafic granulites from the area.

b) Orthopyroxene

Orthopyroxene is euhedral and sometimes porphyroblastic. Orthopyroxene in type A ultramafic granulites is characterized by high X_{Mg} ranging from 0.68 to 0.91. The Al_2O_3 content is commonly less than 1.65%. Meanwhile, orthopyroxene in type B shows low X_{Mg} ranging from 0.49 to 0.73. The Al_2O_3 content is commonly higher than that of orthopyroxene in Type A. One specimen (77011505) contains orthopyroxene with the Al_2O_3 content as high as 6%, which shows distinct pleochroism with a reddish tint. Orthopyroxene in both types sometimes shows chemical zoning. In each zoned crystal, in general, X_{Mg} tends to be unchanged but Al_2O_3 is concentrated more in the core part.

c) Clinopyroxene

Clinopyroxene is usually euhedral. In type A, clinopyroxene is rich in MgO, as in the case of orthopyroxene, and X_{Mg} ranges from 0.78 to 0.91. The Al_2O_3 content is less than 1.66%. Clinopyroxene in type B is poor in MgO and rich in Al_2O_3 in comparison with that in type A. The Al_2O_3 content is in the range from 1.70 to 2.85%. In type B specimens, clinopyroxene is sometimes distinctly zoned and the Al_2O_3 content gradually increases from rim to core in a grain.

Generally speaking, in both types X_{Mg} of clinopyroxene is greater than that of coexisting orthopyroxene.

d) Hornblende

Hornblende in type A usually shows *Z*-axial color of green. The composition of the hornblende ranges from pargasite to edenite (after the criteria by LEAKE, 1978), showing high content in MgO and low in Al_2O_3 in comparison with that in type B. In specimen 77011715, colorless amphibole is found along cleavage planes of clinopyroxene and orthopyroxene, suggesting a retrograde origin. Its composition is rich in tremolite molecules.

Hornblende in type B usually shows variable color from brown to pale green. Generally they are rich in Al_2O_3 and poor in MgO, X_{Mg} ranging from 0.46 to 0.68. They belong to ferroan pargasite to ferroan pargasitic hornblende. Specimen 77011804 contains dark brownish hornblende, which carries high TiO_2 content of 3.17%. Hornblendes in both types frequently show chemical zonation but a distinct tendency of chemical changes from core to rim cannot be observed.

e) Biotite

Biotite in type A has usually a faint tint and is rich in MgO, X_{Mg} reaching 0.90. It has chemical characteristics rich in SiO_2 and poor in Al_2O_3 and TiO_2. While, biotite in type B shows distinct pleochroism with a dark brownish tint, rich in Al_2O_3 and TiO_2 and poor in SiO_2 and MgO. In one specimen (77011505) of type B, brownish biotite which shows high X_{Mg} of 0.82 is included in garnet.

f) Garnet

Garnet is found only in type B. It usually occurs as euhedral crystals including other mafic minerals. The most magnesian garnet has more than 41 mole percent of pyrope molecules. Garnet usually shows a distinctly zoned structure, the core part being generally more magnesian and less manganese than the rim part.

g) Plagioclase

Plagioclase appears only in type B. It usually develops as interstitial crystals. Some specimens contain highly calcic plagioclase with X_{An} over 0.90. Generally, each grain shows distinct reverse-zoning. The compositional ranges (X_{An}) of core and rim parts are 0.41 to 0.92, and 0.83 to 0.96, respectively.

5. Discussion

As shown in the above sections, ultramafic granulites of types A and B in the discussed area have different modes of occurrence and mineralogical characteristics.

For the consideration of compositional relationships among coexisting orthopyroxene, clinopyroxene, hornblende and/or garnet, the CaO-MgO-FeO (Fig. 3) and Al_2O_3-CaO-(MgO+FeO) (Fig. 4) diagrams are used.

It can be seen from Fig. 3 that hornblende and/or garnet systematically change their Fe/Mg ratios with correlation to those of coexisting pyroxenes. In one specimen (77011715, in the figure represented simply as 1715) of type A, occurs tremolitic amphibole which is inferred to be secondary as described before. This is the reason why the join is incompatible with those of the other specimens. In the case of type A, joins

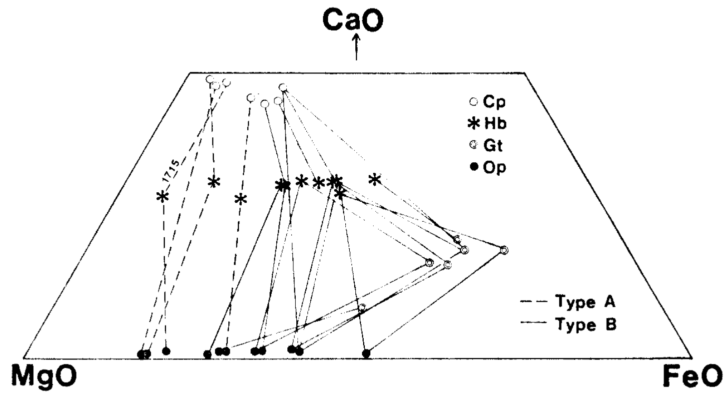

Fig. 3. CaO-MgO-FeO diagram showing the phase relationship among orthopyroxene (Op), clinopyroxene (Cp), calcic amphibole (Hb) and/or garnet (Gt).

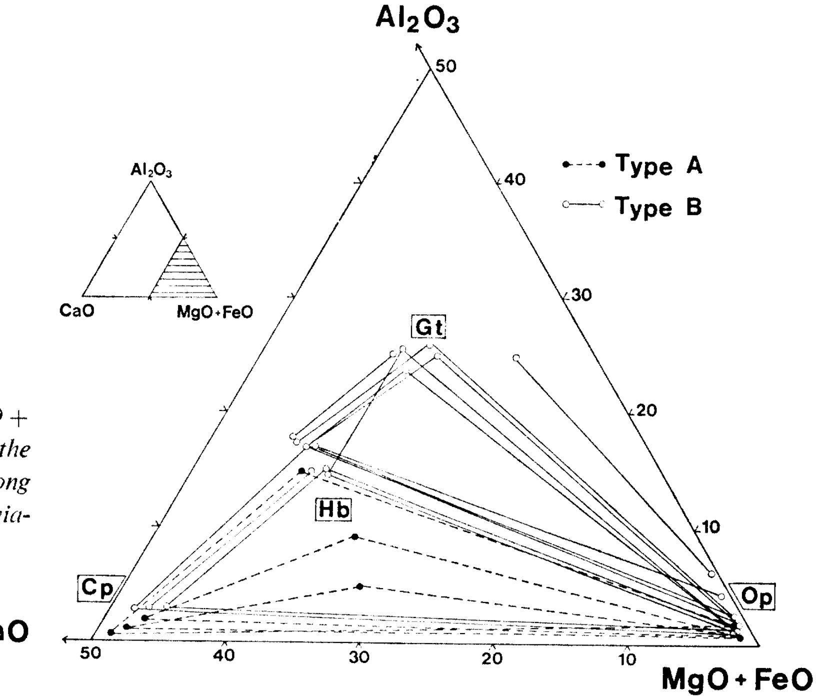

Fig. 4. Al_2O_3-CaO-(MgO+FeO) diagram showing the phase relationship among mafic minerals. Abbreviations are as in Fig. 3.

among two- to three-phases are situated on a more magnesian side than those of type B.

As easily visualized in Fig. 4, the relationship among these mafic minerals is, in general, compatible and orthopyroxene, clinopyroxene and hornblende in garnet-bearing assemblage (type B) are more aluminous than in garnet-free ones (type A).

Figure 5 shows the distribution of Mg and Fe between coexisting orthopyroxene and clinopyroxene in types A and B, indicating that the pairs from both types are plotted on the line of $K_D=0.510$, in spite of the difference in pyroxene compositions between the types described before.

The Fe/Mg distribution of biotite, although not shown here, seems to be changed systematically with correlation to those of coexisting pyroxenes and garnet.

Mineral paragenetic relationships considered suggest that these mafic minerals in both types were in equilibrium with each other under the same physical conditions and that the differences of mineral parageneses and phase chemistries between the two types can be ascribed to the difference in host rock compositions such as the MgO/(MgO+FeO) ratio and the Al_2O_3 content.

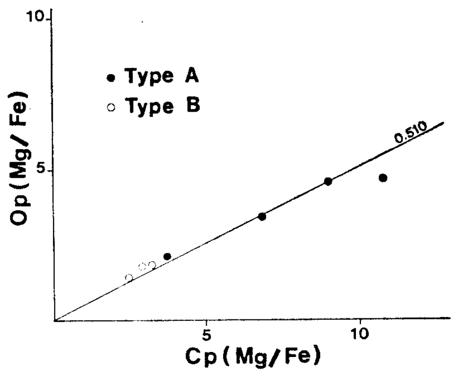

Fig. 5. Mg-Fe distribution between coexisting orthopyroxene (Op) and clinopyroxene (Cp).

Table 2. Temperature estimates based on orthopyroxene-clinopyroxene pairs in the Ongul Islands area.

Specimen No.	a_{Di}^{cpx}	a_{En}^{opx}	x_{Fe}^{opx}	T_1°C	T_2°C
Type A					
77011411	0.016	0.658	0.175	796	706
1509	0.034	0.465	0.308	836	819
1714C*	0.030	0.656	0.178	870	795
1714R*	0.030	0.661	0.176	872	794
1715	0.024	0.574	0.224	825	764
Type B					
77011501	0.029	0.343	0.404	798	805
1612C	0.060	0.392	0.352	902	932
1612R	0.044	0.391	0.358	858	872

* C and R mean core and rim parts, respectively.
T_1: Wood and Banno (1973), T_2: Wells (1977)

The temperature condition is calculated by adopting the orthopyroxene-clinopyroxene geothermometers by Wood and Banno (1973) and Wells (1977). Table 2 shows the representative results based upon the pyroxene pairs whose chemical compositions are given in the Appendix. No systematic difference in the temperature values seems to exist between those estimated from the pairs of core to core and those of rim to rim. In Fig. 6 is represented the distribution of the temperatures calculated above (by Wells's method) together with those obtained from the other pyroxene pairs whose chemical compositions are omitted in Tables A-1 and A-2. Although the obtained values are somewhat scattered, especially those for type B which are rather higher probably due to the effect of higher content of Al_2O_3 in pyroxenes, they seem to be concentrated around 800°C (Fig. 6). Therefore, it seems reasonable to take the value of 800°C as a maximum equilibrium temperature of the ultramafic granulites concerned.

Next, based upon this temperature calculated, the pressure condition is estimated using the garnet-pyroxenes-plagioclase-quartz geobarometer (Perkins and Newton, 1981). As shown in Table 3, the pressure condition ranges from 7.2 to 8.0 kb using the composition of core parts of garnet and plagioclase. It should be noted that the values estimated from the compositions of rim parts of garnet and plagioclase are rather lower. Calculations using clinopyroxene give somewhat low values in comparison with those using orthopyroxene. As described before, the association of olivine

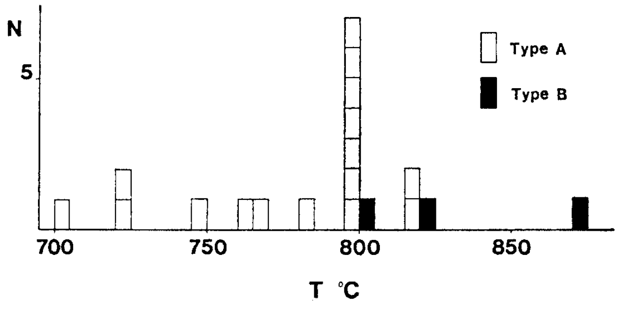

Fig. 6. Histogram showing the equilibrium temperature estimated by the pairs of coexisting orthopyroxene and clinopyroxene (A pair exceeding 900°C is omitted).

Table 3. Pressure estimates based on garnet-pyroxenes-plagioclase-quartz (PERKINS and NEWTON, 1981) in the Ongul Islands area.

Specimen No.	Pl		Gar						Opx		Cpx		P (kb)
	X_{An}	a_{An}	X_{Gr}	X_{Py}	X_{Al}	X_{Sp}	a_{Gr}	a_{Py}	X_{Mg}	a_{En}	X_{Mg}	a_{Di}	
77011501C*	0.811	0.781	0.187	0.236	0.559	0.018	0.217	0.263	0.596	0.342			7.2
											0.717	0.647	4.8
1501R*	0.854	0.811	0.192	0.227	0.561	0.020	0.221	0.255	0.596	0.342			6.8
											0.717	0.647	4.7
1505C	0.736	0.743	0.087	0.433	0.457	0.023	0.118	0.450	0.711	0.454			8.0
1505R	0.841	0.802	0.075	0.410	0.488	0.027	0.100	0.424	0.711	0.454			6.7
1704C	0.463	0.589	0.182	0.175	0.595	0.048	0.203	0.196	0.489	0.222			7.4
1706C	0.555	0.659	0.149	0.272	0.530	0.049	0.177	0.295	0.608	0.351			7.8
1706R	0.833	0.796	0.154	0.247	0.548	0.051	0.180	0.269	0.608	0.351			6.4

* C and R mean core and rim parts, respectively.
Temperature is assumed to be 800°C.

and plagioclase is not found in the ultramafic granulites from the area. This fact should demarcate the lower limit of the pressure condition.

As described before, the constituent minerals such as pyroxenes, garnet and plagioclase show distinct chemical zoning, some of which may suggest the prograde change of metamorphic conditions. The significance of zoning should be further studied in detail.

Summing the above estimations up, it can well be said that the metamorphic conditions deduced from the ultramafic granulites in the Ongul Islands area are around 800°C and 7.5 kb. The conditions seem to be rather higher of grade, especially in temperature, than those previously estimated by the author (1983) from the specimens of Langhovde, Skarvsnes and Skallen areas in the Lützow-Holm Bay region. The discrepancy may partly due to the difference in methods and procedures of the calculations. It is probable that the temperature estimated here may give the maximum value inferred in the Ongul Islands area. The conditions given here seem to be rather consistent with those estimated in the Lützow-Holm Bay region by MOTOYOSHI *et al.* (1984) and KATSUSHIMA (1985).

All things considered, the difference between the two types of ultramafic granulites is inferred to reflect the difference of original rocks emplaced prior to the main phase of the granulite-facies metamorphism, during which the main constituent minerals in both types are formed. Judging from the chemical and modal compositions of minerals, it is probable that the original rocks of type A were rich in MgO and poor in Al_2O_3 as compared with those of type B. This chemical difference as well as the difference of modes of field occurrence must have a key to clarify the origin of ultramafic granulites in the area.

6. Conclusions

Investigations on the field occurrence and mineralogical characteristics of ultramafic granulites in the East and West Ongul Islands area led the author to the following conclusions.

1) The ultramafic granulites can be grouped into two types, A (free from plagioclase and garnet) and B (with plagioclase and/or garnet). Type A tends to occur as isolated blocks in charnockite or hornblende gneiss, and type B as sheeted bodies concordant with surrounding paragneisses and charnockite.

2) Such mafic minerals as orthopyroxene, clinopyroxene and hornblende in type A have the chemical tendency rich in MgO and poor in Al_2O_3 as compared with those in type B.

3) Two types of ultramafic granulites are metamorphosed under the same temperature condition as high as around 800°C. The pressure condition suggested by type B is around 7.5 kb.

4) The difference between the two types can be ascribed to the difference of the original rocks.

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Appendix

Table A-1. Representative chemical compositions of olivine (Ol), orthopyroxene (Op) and clinopyroxene (Cp) in type A ultramafic granulites.

	1 Ol	2 Op	3 Op	4 Op	5 Op	6 Op	7 Cp	8 Cp	9 Cp	10 Cp
SiO_2	38.19	55.03	52.64	54.50	55.12	55.05	53.13	52.96	53.26	54.45
TiO_2	0.03	0.04	0.07	0.05	0.04	0.01	0.05	0.11	0.11	0.05
Al_2O_3	tr.	1.29	0.79	0.74	0.68	0.72	0.59	1.66	0.80	0.98
FeO*	19.87	11.79	19.96	12.03	11.83	14.61	2.90	7.41	3.36	4.21
MnO	0.32	0.26	0.42	0.48	0.54	0.75	0.13	0.14	0.18	0.31
MgO	42.23	31.04	25.22	31.09	31.15	28.50	17.46	14.86	16.99	16.26
CaO	tr.	0.44	0.46	0.37	0.31	0.46	25.29	22.68	23.96	23.84
Na_2O	0.03	0.03	tr.	0.01	tr.	0.03	0.08	0.81	0.24	0.45
K_2O	tr.	0.01	0.03	0.01	0.02	0.02	0.01	0.01	tr.	0.01
Total	100.67	99.93	99.59	99.28	99.69	100.15	99.64	100.64	98.90	100.56
O	4.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000
Si	0.978	1.951	1.950	1.951	1.961	1.975	1.954	1.955	1.969	1.983
Ti	0.001	0.001	0.002	0.001	0.001	0.000	0.001	0.003	0.003	0.001
Al	—	0.054	0.035	0.031	0.029	0.030	0.026	0.072	0.035	0.042
Fe	0.425	0.349	0.619	0.360	0.352	0.439	0.089	0.229	0.104	0.128
Mn	0.007	0.008	0.013	0.014	0.016	0.023	0.004	0.004	0.006	0.010
Mg	1.611	1.640	1.393	1.659	1.652	1.524	0.957	0.817	0.936	0.883
Ca	—	0.017	0.018	0.014	0.012	0.018	0.997	0.897	0.949	0.930
Na	0.001	0.002	—	0.001	—	0.002	0.006	0.058	0.017	0.032
K	—	0.001	0.001	0.000	0.001	0.001	0.000	0.001	—	0.000
mg	0.79	0.82	0.69	0.82	0.82	0.78	0.91	0.78	0.90	0.87
Sp. No.**	7701 1411	7701 1411	7701 1509	7701 1714C	7701 1714R	7701 1715	7701 1411	7701 1509	7701 1714	7701 1715

* Total Fe as FeO. ** C and R mean core and rim parts, respectively.

Table A-2. Representative chemical compositions of orthopyroxene (Op) and clinopyroxene (Cp) in type B ultramafic granulites.

	1 Op	2 Op	3 Op	4 Op	5 Op	6 Op	7 Op	8 Op	9 Op	10 Cp	11 Cp	12 Cp	13 Cp	14 Cp
SiO_2	51.26	49.60	54.31	54.88	52.32	51.92	48.96	51.44	52.35	51.29	50.83	50.87	51.69	52.95
TiO_2	0.10	0.11	0.04	0.02	0.11	0.13	0.10	0.07	0.04	0.20	0.30	0.25	0.39	0.25
Al_2O_3	1.21	6.30	4.03	3.88	1.46	1.21	0.84	1.46	1.93	2.06	2.85	2.35	2.72	1.70
FeO*	25.73	18.28	16.80	16.76	22.14	22.50	30.86	24.47	21.14	9.64	8.77	7.87	9.75	7.43
MnO	0.27	0.27	0.59	0.56	0.90	0.94	1.10	0.79	0.70	0.11	0.41	0.39	0.23	0.24
MgO	21.29	25.23	24.24	24.23	22.83	22.68	16.55	21.28	23.51	13.71	14.20	14.38	13.21	14.37
CaO	0.59	0.12	0.27	0.27	0.65	0.52	0.67	0.42	0.47	23.36	21.15	22.15	21.24	22.97
Na_2O	0.02	tr.	0.02	tr.	tr.	tr.	0.09	tr.	tr.	0.33	0.37	0.34	0.59	0.41
K_2O	0.01	0.02	0.01	tr.	0.03	0.03	0.05	0.02	0.01	0.01	0.04	0.05	0.04	0.03
Total	100.48	99.93	100.31	100.60	100.44	99.93	99.22	99.95	100.15	100.71	98.92	98.65	99.86	100.35
O	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000
Si	1.935	1.817	1.954	1.965	1.945	1.945	1.935	1.943	1.939	1.918	1.918	1.923	1.936	1.959
Ti	0.003	0.003	0.001	0.001	0.003	0.004	0.003	0.002	0.001	0.006	0.009	0.007	0.011	0.007
Al	0.054	0.272	0.171	0.164	0.064	0.053	0.039	0.065	0.084	0.091	0.127	0.105	0.120	0.074
Fe	0.812	0.560	0.505	0.502	0.688	0.705	1.020	0.773	0.655	0.301	0.277	0.249	0.306	0.230
Mn	0.009	0.008	0.018	0.017	0.028	0.030	0.037	0.025	0.022	0.003	0.013	0.013	0.007	0.007
Mg	1.198	1.378	1.299	1.293	1.265	1.266	0.975	1.198	1.298	0.764	0.798	0.810	0.737	0.793
Ca	0.024	0.005	0.010	0.010	0.026	0.021	0.028	0.017	0.019	0.936	0.855	0.897	0.852	0.911
Na	0.001	—	0.001	—	—	—	0.007	—	—	0.024	0.027	0.025	0.043	0.029
K	0.001	0.001	0.000	—	0.001	0.001	0.002	0.001	0.001	0.001	0.002	0.002	0.002	0.001
mg	0.59	0.71	0.72	0.72	0.65	0.64	0.49	0.61	0.66	0.72	0.74	0.76	0.71	0.78
Sp. No.**	7701 1501	7701 1505	7701 1506C	7701 1506R	7701 1612C	7701 1612R	7701 1704	7701 1706	7701 1707	7701 1501	7701 1612C	7701 1612R	7701 1804C	7701 1804R

* Total Fe as FeO.

** C and R mean core and rim parts, respectively.

Table A-3. Representative chemical compositions of amphiboles in types A and B ultramafic granulites.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	41.85	45.61	55.52	39.71	44.19	43.50	37.89	37.82	42.03	42.25	40.83	40.56	40.88	40.44	40.17
TiO_2	0.57	0.80	0.07	2.04	0.29	0.27	2.10	1.68	1.85	1.99	1.97	0.82	0.45	3.13	3.17
Al_2O_3	13.54	7.81	1.76	14.17	14.21	14.30	15.18	14.69	12.11	12.18	11.66	14.64	14.85	12.32	12.48
FeO*	6.82	9.86	4.14	15.42	11.35	11.37	17.12	16.70	12.42	12.94	16.14	15.21	12.98	14.40	14.40
MnO	0.04	0.10	0.11	0.07	0.19	0.15	0.25	0.22	0.28	0.31	0.27	0.23	0.20	0.18	0.21
MgO	16.69	16.25	21.55	10.29	12.84	12.84	8.32	8.84	12.82	12.71	10.36	10.79	11.89	11.43	11.23
CaO	13.13	11.95	12.77	11.89	11.63	11.51	11.59	11.47	11.56	11.76	11.29	11.98	12.26	11.91	11.85
Na_2O	1.96	1.90	0.40	2.14	1.96	1.98	1.02	0.98	1.52	1.54	1.89	1.67	1.98	1.71	1.76
K_2O	1.51	0.86	0.12	1.53	1.08	1.05	2.79	2.82	1.56	1.66	1.61	2.11	2.14	1.91	1.84
Total	96.11	95.14	96.44	97.26	97.74	96.97	96.26	95.22	96.15	97.34	96.02	98.01	97.63	97.43	97.11
O	23.000	23.000	23.000	23.000	23.000	23.000	23.000	23.000	23.000	23.000	23.000	23.000	23.000	23.000	23.000
Si	6.168	6.813	7.782	6.024	6.442	6.397	5.892	5.937	6.325	6.300	6.287	6.096	6.112	6.109	6.089
Al^{IV}	1.832	1.187	0.218	1.976	1.558	1.603	2.108	2.063	1.675	1.700	1.713	1.904	1.888	1.891	1.911
(Tet)	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al^{VI}	0.521	0.189	0.073	0.558	0.884	0.877	0.675	0.656	0.473	0.442	0.403	0.690	0.729	0.303	0.320
Fe	0.751	1.193	0.417	1.884	1.295	1.279	2.150	2.078	1.443	1.509	1.991	1.802	1.572	1.768	1.780
Mg	3.665	3.618	4.503	2.325	2.789	2.814	1.929	2.068	2.875	2.825	2.378	2.416	2.649	2.573	2.538
Ti	0.063	0.089	0.007	0.233	0.032	0.030	0.246	0.198	0.209	0.224	0.228	0.092	0.050	0.356	0.362
Mn	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
(M_1–M_3)	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
Ca	1.905	1.913	1.918	1.919	1.816	1.813	1.891	1.856	1.844	1.856	1.862	1.860	1.924	1.925	1.925
Mn	0.005	0.012	0.013	0.009	0.024	0.019	0.033	0.029	0.036	0.039	0.035	0.030	0.025	0.024	0.027
Fe	0.090	0.039	0.069	0.072	0.089	0.120	0.076	0.115	0.120	0.105	0.087	0.110	0.051	0.051	0.045
Na	—	0.036	—	—	0.071	0.048	—	—	—	—	0.016	—	—	—	0.003
(M_4)	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Ca	0.169	—	—	0.013	—	—	0.041	0.073	0.020	0.024	—	0.069	0.040	0.003	—
Na	0.561	0.515	0.108	0.630	0.483	0.517	0.308	0.298	0.444	0.447	0.548	0.487	0.573	0.502	0.516
K	0.284	0.163	0.021	0.296	0.200	0.197	0.554	0.564	0.299	0.316	0.317	0.405	0.407	0.369	0.355
(A)	1.014	0.678	0.129	0.939	0.683	0.714	0.903	0.935	0.763	0.787	0.865	0.961	1.020	0.874	0.871
mg	0.81	0.75	0.90	0.54	0.67	0.67	0.46	0.49	0.65	0.64	0.53	0.56	0.62	0.59	0.58
Sp. No.**	7701 1411	7701 1509	7701 1715	7701 1501	7701 1506C	7701 1506R	7701 1610C	7701 1610R	7701 1612C	7701 1612R	7701 1704	7701 1706	7701 1707	7701 1804C	7701 1804R

1 to 3: Type A, 4 to 15: Type B. * Total Fe as FeO. ** C and R mean core and rim parts, respectively.

Table A-4. Representative chemical compositions of biotite in types A and B ultramafic granulites.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	37.23	39.44	40.67	36.27	36.47	35.93	36.71	36.85	36.83	35.90	38.20	36.75	37.54	37.00
TiO_2	2.72	1.97	1.09	1.88	3.29	3.39	3.92	3.94	4.79	4.81	1.29	0.82	5.56	5.72
Al_2O_3	13.76	13.52	13.60	15.01	15.83	16.51	15.37	15.21	14.69	13.04	14.99	15.12	14.21	14.02
FeO*	10.70	4.43	5.15	20.89	11.11	7.63	15.17	15.61	13.57	17.47	12.70	11.96	12.50	13.38
MnO	0.04	0.01	0.04	0.01	tr.	tr.	0.12	0.15	0.12	0.10	0.07	tr.	0.09	0.12
MgO	18.60	22.66	23.30	11.63	17.95	19.35	14.59	14.23	15.53	13.55	18.33	18.77	16.03	15.13
CaO	tr.	tr.	tr.	tr.	0.01	0.04	0.02	0.05	tr.	0.04	tr.	0.03	tr.	0.01
Na_2O	0.40	0.22	0.10	0.06	0.57	0.84	0.02	0.02	0.18	0.15	0.13	0.27	0.13	0.10
K_2O	9.44	9.82	9.80	9.69	8.39	8.17	9.39	9.17	9.66	9.43	9.61	9.69	9.71	9.54
Total	92.89	92.07	93.75	95.44	93.62	91.86	95.31	95.23	95.37	94.49	95.32	93.41	95.77	95.02
O	22.000	22.000	22.000	22.000	22.000	22.000	22.000	22.000	22.000	22.000	22.000	22.000	22.000	22.000
Si	5.611	5.796	5.870	5.581	5.428	5.361	5.491	5.521	5.483	5.515	5.636	5.541	5.531	5.521
Al^{IV}	2.389	2.204	2.130	2.419	2.572	2.639	2.509	2.479	2.517	2.362	2.364	2.459	2.469	2.465
(Z)	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	7.877	8.000	8.000	8.000	7.986
Al^{VI}	0.055	0.138	0.184	0.305	0.206	0.266	0.202	0.208	0.061	—	0.244	0.229	—	—
Ti	0.308	0.218	0.118	0.218	0.369	0.380	0.441	0.444	0.536	0.556	0.144	0.093	0.616	0.642
Fe	1.349	0.545	0.622	2.689	1.332	0.952	1.899	1.956	1.689	2.245	1.568	1.507	1.541	1.670
Mn	0.005	0.002	0.005	0.002	—	—	0.015	0.019	0.016	0.013	0.008	—	0.011	0.015
Mg	4.177	4.962	5.012	2.667	3.981	4.304	3.252	3.177	3.447	3.103	4.031	4.217	3.520	3.365
(Y)	5.894	5.865	5.941	5.881	5.938	5.902	5.809	5.804	5.749	5.917	5.995	6.046	5.688	5.692
Ca	—	—	—	—	0.001	0.006	0.004	0.008	—	0.006	—	0.004	—	0.001
Na	0.116	0.062	0.028	0.017	0.164	0.244	0.007	0.007	0.052	0.045	0.037	0.080	0.036	0.030
K	1.815	1.840	1.804	1.902	1.594	1.555	1.792	1.752	1.835	1.849	1.809	1.864	1.826	1.817
(X)	1.931	1.902	1.832	1.919	1.759	1.799	1.803	1.767	1.887	1.900	1.846	1.948	1.862	1.848
mg	0.76	0.90	0.89	0.50	0.74	0.82	0.63	0.62	0.67	0.58	0.72	0.74	0.70	0.67
Sp. No.**	7701 1509	7701 1714	7701 1715	7701 1501†	7701 1505	7701 1505††	7701 1610C	7701 1610R	7701 1612	7701 1704	7701 1706	7701 1707	7701 1804C	7701 1804R

1 to 3: Type A, 4 to 14: Type B. * Total Fe as FeO. ** C and R mean core and rim parts, respectively. † secondary. †† included in garnet.

Table A-5. Representative chemical compositions of garnet in type B ultramafic granulites.

	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	38.01	39.01	39.44	39.39	38.94	38.78	37.63	38.00	38.44	37.93	38.82	38.16
TiO_2	0.09	0.08	0.07	0.03	0.10	0.09	0.07	0.08	0.04	0.06	0.04	0.03
Al_2O_3	21.17	21.32	22.38	22.57	20.75	20.81	21.61	21.47	21.82	21.67	22.48	21.93
FeO*	26.55	26.59	22.51	23.41	24.59	24.77	27.87	28.18	25.71	26.20	22.56	23.62
MnO	0.84	0.96	1.12	1.27	1.36	1.45	2.20	2.52	2.35	2.42	1.90	2.30
MgO	6.29	6.03	11.95	11.04	6.12	6.31	4.60	4.19	7.41	6.64	8.88	7.77
CaO	6.91	7.12	3.35	2.82	7.27	6.98	6.64	6.81	5.62	5.76	5.87	5.91
Na_2O	tr.	0.01	tr.	tr.	0.02	0.01	tr.	0.02	tr.	0.01	0.01	tr.
K_2O	0.02	0.01	0.02	0.01	0.03	0.04	0.02	0.03	0.02	0.02	0.03	0.03
Total	99.88	101.13	100.84	100.54	99.18	99.24	100.64	101.30	101.41	100.71	100.59	99.75
O	24.000	24.000	24.000	24.000	24.000	24.000	24.000	24.000	24.000	24.000	24.000	24.000
Si	5.951	6.020	5.926	5.950	6.093	6.069	5.914	5.947	5.911	5.899	5.917	5.917
Ti	0.011	0.009	0.007	0.004	0.012	0.011	0.008	0.009	0.005	0.007	0.004	0.004
Al	3.908	3.878	3.965	4.019	3.828	3.840	4.003	3.961	3.955	3.973	4.039	4.008
Fe	3.477	3.432	2.829	2.958	3.217	3.242	3.662	3.688	3.306	3.407	2.876	3.063
Mn	0.112	0.125	0.142	0.162	0.180	0.192	0.293	0.335	0.307	0.319	0.245	0.302
Mg	1.468	1.388	2.675	2.486	1.428	1.471	1.077	0.977	1.697	1.538	2.017	1.796
Ca	1.159	1.177	0.539	0.457	1.218	1.170	1.118	1.141	0.925	0.959	0.959	0.982
Na	—	0.003	—	—	0.005	0.003	—	0.006	—	0.004	0.002	—
K	0.003	0.003	0.003	0.003	0.006	0.007	0.005	0.007	0.004	0.004	0.005	0.005
X_{Py}	0.236	0.227	0.433	0.410	0.236	0.242	0.175	0.159	0.272	0.247	0.331	0.292
X_{Al}	0.559	0.561	0.457	0.488	0.532	0.534	0.595	0.601	0.530	0.548	0.472	0.499
X_{Sp}	0.018	0.020	0.023	0.027	0.030	0.032	0.048	0.054	0.049	0.051	0.040	0.049
X_{Gr}	0.187	0.192	0.087	0.075	0.202	0.192	0.182	0.186	0.149	0.154	0.157	0.160
Sp. No.**	7701 1501C	7701 1501R	7701 1505C	7701 1505R	7701 1610C	7701 1610R	7701 1704C	7701 1704R	7701 1706C	7701 1706R	7701 1707C	7701 1707R

* Total Fe as FeO.

** C and R mean core and rim parts, respectively.

Table A-6. *Representative chemical compositions of plagioclase in type B ultramafic granulites.*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	47.78	45.73	48.04	45.60	44.81	43.69	53.47	46.54	55.52	54.19	46.72	45.24	44.27	57.83
TiO_2	0.02	tr.	0.02	0.01	0.03	0.03	0.01	0.04	0.02	tr.	0.02	tr.	tr.	0.03
Al_2O_3	33.19	33.55	30.56	32.37	36.37	36.97	28.99	34.00	25.85	28.22	33.05	33.01	33.57	26.58
FeO*	tr.	0.19	0.03	0.07	0.29	0.26	0.19	0.32	tr.	0.03	0.18	tr.	0.01	0.09
MnO	tr.	tr.	tr.	tr.	0.11	0.09	0.06	0.09	tr.	tr.	tr.	tr.	tr.	0.06
MgO	0.18	tr.	tr.	0.01	0.02	0.02	0.03	0.02	tr.	tr.	tr.	tr.	0.01	0.01
CaO	17.08	18.67	15.99	18.01	18.84	19.86	11.56	17.39	10.12	12.09	18.03	19.02	19.75	8.47
Na_2O	2.16	1.73	3.14	1.87	0.93	0.47	4.88	1.58	6.35	5.22	1.96	1.32	0.94	6.43
K_2O	0.07	0.04	0.03	0.02	0.07	0.03	0.18	0.05	0.22	0.20	0.05	0.02	0.01	0.46
Total	100.48	99.91	97.81	97.96	101.47	101.42	99.37	100.03	98.08	99.95	100.01	98.61	98.56	99.96
O	32.000	32.000	32.000	32.000	32.000	32.000	32.000	32.000	32.000	32.000	32.000	32.000	32.000	32.000
Si	8.743	8.479	9.027	8.604	8.171	7.994	9.738	8.568	10.219	9.826	8.626	8.495	8.336	10.370
Ti	0.003	—	0.003	0.002	0.005	0.004	0.002	0.005	0.003	—	0.003	—	—	0.004
Al	7.159	7.333	6.770	7.201	7.818	7.975	6.225	7.378	5.610	6.034	7.194	7.308	7.453	5.619
Fe	—	0.029	0.005	0.011	0.044	0.040	0.028	0.049	—	0.005	0.027	—	0.002	0.014
Mn	—	—	—	—	0.016	0.014	0.009	0.014	—	—	—	—	—	0.009
Mg	0.050	—	—	0.002	0.007	0.005	0.007	0.005	—	0.001	—	—	0.003	0.004
Ca	3.349	3.709	3.219	3.642	3.682	3.894	2.256	3.431	1.995	2.349	3.568	3.826	3.984	1.628
Na	0.766	0.624	1.144	0.685	0.327	0.167	1.722	0.564	2.264	1.836	0.701	0.482	0.344	2.236
K	0.017	0.010	0.007	0.004	0.016	0.007	0.043	0.012	0.051	0.047	0.012	0.006	0.001	0.105
X_{An}	0.811	0.854	0.736	0.841	0.915	0.957	0.561	0.856	0.463	0.555	0.833	0.887	0.920	0.410
X_{Ab}	0.185	0.144	0.262	0.158	0.081	0.041	0.428	0.141	0.525	0.434	0.164	0.112	0.080	0.563
X_{Or}	0.004	0.002	0.002	0.001	0.004	0.002	0.011	0.003	0.012	0.011	0.012	0.001	0.000	0.027
Sp. No.**	7701 1501C	7701 1501R	7701 1505C	7701 1505R	7701 1610C	7701 1610R	7701 1612C	7701 1612R	7701 1704C	7701 1706C	7701 1706R	7701 1707C	7701 1707R	7701 1804R

* Total Fe as FeO.

** C and R mean core and rim parts, respectively.